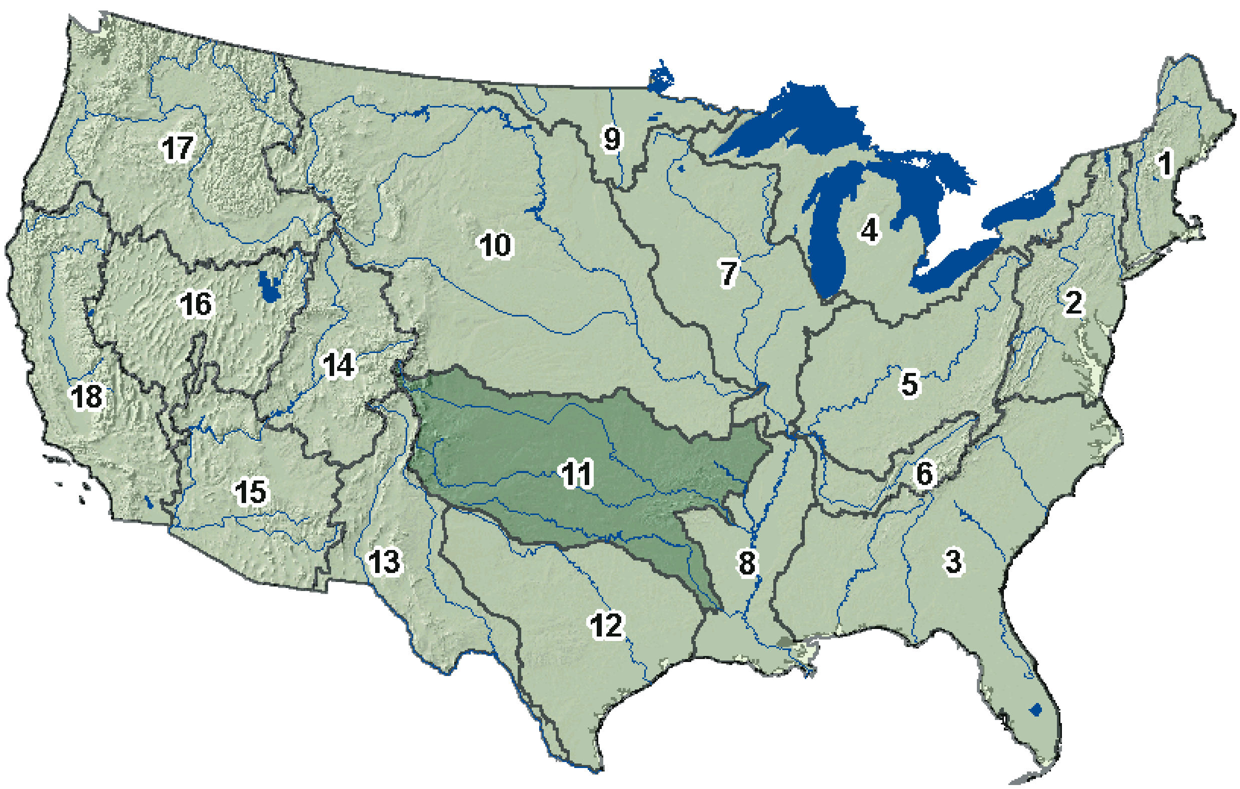
DOE/ID-11019
July 2002

Low Head/Low Power Hydropower Resource Assessment of the Arkansas White Red Hydrologic Region



DOE/ID-11019

Low Head/Low Power Hydropower Resource Assessment of the Arkansas White Red Hydrologic Region

Douglas G. Hall, INEEL
Gregory R. Carroll, BNI
Shane J. Cherry, INEEL
Randy D. Lee, INEEL
Garold L. Sommers, INEEL

Published July 2002

Prepared for the
U.S. Department of Energy
Idaho Operations Office

ABSTRACT

An analytical assessment of the hydropower potential of the Arkansas White Red Hydrologic Region was performed using state-of-the-art digital elevation models and geographic information system tools. The principal focus of the study was the amount of low head (less than 30 ft)/low power (less than 1 MW) potential in the region and the fractions of this potential that corresponded to the operating envelopes of three classes of hydropower technologies: conventional turbines, unconventional systems, and microhydro (less than 100 kW) technologies. To obtain these estimates, the hydropower potential of all the stream segments in the region, which averaged 2 miles in length, were calculated. These calculations were performed using hydrography and hydraulic heads that were obtained from the U.S. Geological Survey's Elevation Derivatives for National Applications dataset and stream flow predictions from a regression equation developed specifically for the region. Stream segments excluded from development and developed hydropower in the region were accounted for to produce estimates of available total hydropower potential and low head/low power potential. The available low head/low power potential was divided into potentials corresponding to the three classes of technologies, and the geographic locations of these sites were mapped.

SUMMARY

The U.S. Department of Energy (DOE) has had an ongoing interest in assessing the hydropower potential of the United States. Previous assessments have focused on potential projects that have a capacity of 1 MW and above. These assessments were also based on previously identified sites with a recognized, although varying, level of development potential. In FY 2000, DOE initiated planning for an assessment of hydropower potential for low head (30 feet or less) and low power (1 MW or less) resources.

The Idaho National Engineering and Environmental Laboratory in conjunction with the U.S. Geological Survey recently completed a pilot low head/low power hydropower resource assessment. The principal objective of this pilot study was to develop and demonstrate a method of estimating the hydropower potential of a large geographic area; in this case, the Arkansas White Red (AWR) Hydrologic Region. The method that was developed uses state-of-the-art digital elevation models and geographic information system tools to assess the hydropower potential of every stream segment within a chosen study area.. Summing the estimated hydropower potential of all the stream segments in the region provided an estimate of the total hydropower of the region. Stream segments that had power potentials less than 1 MW were segregated and summed to provide an estimate of total low head/low power potential in the region. Having hydropower potential estimates in such small increments allowed the regional low head/low power potential to be further divided to determine the amounts of potential corresponding to the operating envelopes of three classes of low head/low power hydropower technologies: conventional turbines, unconventional systems, and microhydro technologies.

In order to calculate the hydropower potential of each stream segment, the hydrography in the region was derived using the U.S. Geological Survey's Elevation Derivatives for National Applications (EDNA) dataset. In addition to the hydrography, the dataset provided elevation data at the upstream and downstream ends of each stream segment, which were used to calculate hydraulic head. The dataset also allowed the calculation of the drainage area providing runoff to each stream segment. Overlaying the EDNA data with climatic data from the Parameter-elevation Regressions on Independent Slopes Model dataset provided the variables needed to calculate stream flow for each stream segment using a regression equation developed specifically for the region. Combining stream flow with hydraulic head provided the hydropower potential of the stream segment.

Because the hydrography used was "synthetic," stream segments were compared to streams in the U.S. Geological Survey's National Hydrography Dataset. Unconfirmed stream segments were eliminated from the datasets that were used to estimate total hydropower potentials. A geographic information system layer containing streams and areas that are excluded from development by statutory regulations was used to segregate excluded and nonexcluded stream segments. The amount of developed hydropower in the region provided by the Federal Energy Regulatory Commission was subtracted from total, nonexcluded, hydropower potentials to produce estimates of available hydropower potentials.

The assessment estimated that the total hydropower potential of the AWR Region is 5,000 MW. Of this amount, 130 MW is excluded from development. With 2,000 MW of developed hydropower in the region, the total available hydropower potential is estimated to be about 3,000 MW. Low head/low power potential makes up 2,000 MW of the total available potential. Division of the available low head/low power potential amongst low head/low power technology classes showed that 40% fell within the operating envelope of conventional turbines, 20% fell within the operating envelope of unconventional systems, and 40% fell within the operating envelope of microhydro technologies. A map of the locations of low head/low power sites by technology class shows a significant density of sites for all three technology classes in the Eastern half of the region. Many sites are found along the major rivers throughout the region as expected.

We concluded from this study that the technical approach we developed is a viable method for estimating the hydropower potential of a large geographic area. Applied to all the hydrologic regions in the continental U.S. it would provide a reasonable estimate of the total available hydropower potential of the country as well as the geographic distribution of this potential. The study showed that there is a significant, available hydropower potential in the AWR Region of which 40% could be realized using existing turbine technology.

We recommend that a similar study be performed using the Pacific Northwest Hydrologic Region (HUC 17) as the study area because of its contrasting topography and hydrography. At the same time, efforts should be made to better establish and improve the accuracy of results. If the results of the HUC 17 are reasonable, we recommend that the assessment of all remaining hydrologic regions in the conterminous U.S. be undertaken.

For further information or comments, please contact:

Douglas G. Hall, Project Manager
Low Head/Low Power Hydropower Resource Assessment Project
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625, MS 3850
Idaho Falls, ID 83415-3850
Phone: (208) 526-9525
E-mail: ***dgh@inel.gov***

Garold L. Sommers, Program Manager
Hydropower Program
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625, MS 3830
Idaho Falls, ID 83415-3830
Phone: (208) 526-1965
E-mail: ***sommergl@inel.gov***

ACKNOWLEDGMENTS

The authors acknowledge and express their appreciation of the contributions to this study made by the U. S. Geological Survey (USGS): the Earth Resources Observation Systems (EROS) Data Center for producing the Elevation Derivatives for National Applications dataset for the Arkansas White Red Hydrologic region and overlaying this dataset with climatic data, Mr. A. H. Rea of the Boise field office for programming and producing the basic hydropower potential dataset used in the study, and Mr. K. G. Ries for being the USGS liaison to the Idaho National Engineering and Environmental Laboratory (INEEL) for the project. The authors also acknowledge and express their appreciation of the technical guidance provided by Mr. R. T. Hunt (INEEL) and the review of this report by Mr. J. Flynn of the U.S. Department of Energy (DOE). Particular acknowledgment and appreciation is expressed for the foresight and guidance of Ms. P. A. Brookshier of the DOE Idaho Operations Office for requesting the assessment reported herein and guiding its development.

CONTENTS

FIGURES

TABLES

ACRONYMS

AWR Arkansas White Red

DOE U.S. Department of Energy

EDNA Elevation Derivatives for National Applications

An analytically derived, three-dimensional dataset in which hydrologic features have been determined based on elevation data from the NED resulting in three dimensional representations of "synthetic streams" (stream path coordinates plus corresponding elevations) and an associated catchment boundary for each synthetic reach (based on 1:24K-scale data for the conterminous US and 1:63,360-scale data for Alaska) (***Note: EDNA synthetic stream reaches do not uniformly coincide with NHD reaches. Conflation of EDNA and NHD features to improve the quality of both datasets is a later phase EDNA development.) (http://mn.water.usgs.gov/uzig/eros.reed.doc)***

FERC Federal Energy Regulatory Commission

GIS Geographic Information System

A set of digital geographic information such as map layers and elevation data layers, that can be analyzed using both standardized data queries as well as spatial query techniques.

HUC hydrologic unit code

INEEL Idaho National Engineering and Environmental Laboratory

NED National Elevation Data

A three-dimensional representation of topographic features composed of geographic coordinates on a 30-m grid with corresponding elevations that numerically represent the topography based on 1:24K-scale data for the conterminous U.S. and 1:63,360-scale data for Alaska (available for the entire U.S. from USGS). ***(http://gisdata.usgs.net/ned/)***

NHD National Hydrography Dataset

A comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs, and wells. ***(http://nhd.usgs.gov)***

PRISM Parameter-elevation Regressions on Independent Slopes Model

An expert system that uses point data and a digital elevation model to generate gridded estimates of climate parameters. ***(http://www.ocs.orst.edu/prism/overview.html)***

NOMENCLATURE

Catchment	That portion on a drainage basin supplying runoff to a particular stream reach.
Drainage Area	The total surface area of the topography of a drainage basin.
Drainage Basin	The geographic area supplying runoff to a particular point on a stream equal to the area of all of the catchments associated with upstream stream reaches connected to the point.
EDNA Stream Node	Starting point of an EDNA synthetic stream, a confluence, or an intermediate point on an EDNA stream defined as a result of having 5,000 National Elevation Data tiles (30×30 m) supplying runoff to the portion of an EDNA synthetic stream between this point and the EDNA node immediately upstream (Note: Each node has an associated catchment and is a pour point.)
EDNA Stream Reach	That portion of a EDNA synthetic stream between two EDNA stream nodes.
Pour Point Flow	The estimated flow of a stream reach equal to the runoff from the corresponding drainage basin.

Low Head/Low Power Hydropower Resource Assessment of the Arkansas White Red Hydrologic Region

1. INTRODUCTION

In June 1989, the U.S. Department of Energy (DOE) initiated the development of a National Energy Strategy to identify the energy resources available to support the expanding demand for the energy in the United States. Past efforts to identify and measure the undeveloped hydropower capacity in the U.S. have resulted in estimates ranging from about 70,000 MW to almost 600,000 MW. The Federal Energy Regulatory Commission's (FERC's) estimate was about 70,000 MW, and the U.S. Army Corps of Engineers' theoretical estimate was 580,000 MW. Public hearings conducted as part of the strategy development process indicated that the undeveloped hydropower resources were not well defined. One of the reasons was that no agency had previously estimated the undeveloped hydropower capacity based on site characteristics, stream flow data, and available hydraulic heads.

As a result, DOE established an interagency Hydropower Resources Assessment Team to ascertain the country's undeveloped hydropower potential. The team consisted of representatives from each power marketing administration (Alaska Power Administration, Bonneville Power Administration, Western Area Power Administration, Southwestern Power Administration, and Southeastern Power Administration), the Bureau of Reclamation, the Army Corps of Engineers, the FERC, the Idaho National Engineering and Environmental Laboratory (INEEL), and the Oak Ridge National Laboratory. The interagency team drafted a preliminary assessment of potential hydropower resources in February 1990. This assessment estimated that 52,900 MW of undeveloped hydropower energy existed in the United States.

Partial analysis of the hydropower resource database by groups in the hydropower industry indicated that the hydropower data included redundancies and errors that reduced confidence in the published estimates of developable hydropower capacity. DOE has continued assessing hydropower resources to correct these deficiencies, improve estimates of developable hydropower, and determine future policy. Modeling of the undeveloped hydropower resources in the United States, based on environmental, legal, and institutional constraints, has identified 5,677 sites that have a total undeveloped capacity of about 30,000 MW.

The previous resource assessments have focused on potential projects that have a capacity of 1 MW and above. DOE identified a need to assess the U.S. hydropower resources for projects of less than 1 MW. In FY 2000, DOE initiated planning for an assessment of hydropower potential for low head (30 feet or less) and low power (1 MW or less) resources. The INEEL in conjunction with the U.S. Geological Survey recently completed the pilot low head/low power hydropower resource assessment reported in this document. The principal objective of this pilot study was to develop and demonstrate a method of estimating the hydropower potential of a large geographic area. The method that was developed uses state-of-the-art digital elevation models and geographic information system tools. Using this method, the hydropower potential of every stream segment within a chosen study area is assessed. Summing the estimated hydropower potential of all the stream segments in the area provides an estimate of the total hydropower of the area.

The study area chosen for the pilot study was the Arkansas White Red (AWR) Hydrologic Region, an area encompassing the entire state of Oklahoma and parts of seven adjacent states. Having hydropower potential estimates in such small increments allowed the regional potential to be divided into total amounts of high power (greater that 1 MW) and low head/low power (generally less than 1 MW and 30 ft of hydraulic head or less) potential. It also allowed the low head/low power potential to be further divided to determine the amounts of potential corresponding to the operating envelopes of three classes of low head/low power hydropower technologies. A by-product of the study, which was focused on low head/low power assessment, is a means of producing the most comprehensive estimate of the hydropower potential of the conterminous and ultimately the continental U.S. and the distribution of this potential than has ever been achieved.

This report is organized by presenting a description of the study area, details of the technical method that was developed and employed to perform the resource assessment, and the results of the assessment. It ends with conclusions based on the results and recommendations for further research and refinement of the technical method.

2. STUDY AREA—ARKANSAS WHITE RED HYDROLOGIC REGION

The AWR Hydrologic Region is one of 21 hydrologic regions in the United States. The conterminous United States is divided in 18 hydrologic regions as shown in Figure 1 with the remaining three regions being Alaska, Hawaii, and Puerto Rico. The hydrologic regions have been numbered using a hydrologic unit code (HUC) of 1 through 21. The AWR Region has been assigned a hydrologic unit code of 11 and is sometimes referred to as "HUC 11." The terms "HUC 11" and "AWR Region" are used interchangeably.

The AWR Region shown in Figure 2 was chosen for this study because it was the first hydrologic region for which Elevation Derivatives for National Applications (EDNA) data were available. The region is composed of three watersheds: the Arkansas River and its major tributary, the Canadian River; the Red River; and the White River. The AWR Region covers the entire state of Oklahoma as well as portions of seven nearby states (Texas, New Mexico, Colorado, Kansas, Missouri, Arkansas, and Louisiana).

The topography over much of the AWR Region is relatively flat, with some notable exceptions. Most of the region falls within the southern Great Plains and is characterized by either flat plains or rolling hills broken by stream floodplains. Higher relief is found in the Ozark Plateau and Ouachita Mountains in the eastern portion of the region where the states of Arkansas, Oklahoma, and Missouri meet. The westernmost part of the region extends all the way to the headwaters of the Arkansas and Canadian Rivers. The upper portions of these watersheds border the continental divide in Colorado and New Mexico. This part of the AWR Region contains topography characteristic of the southern Rocky Mountains: high plateaus and mountains incised by steep canyons and separated by deep valleys.

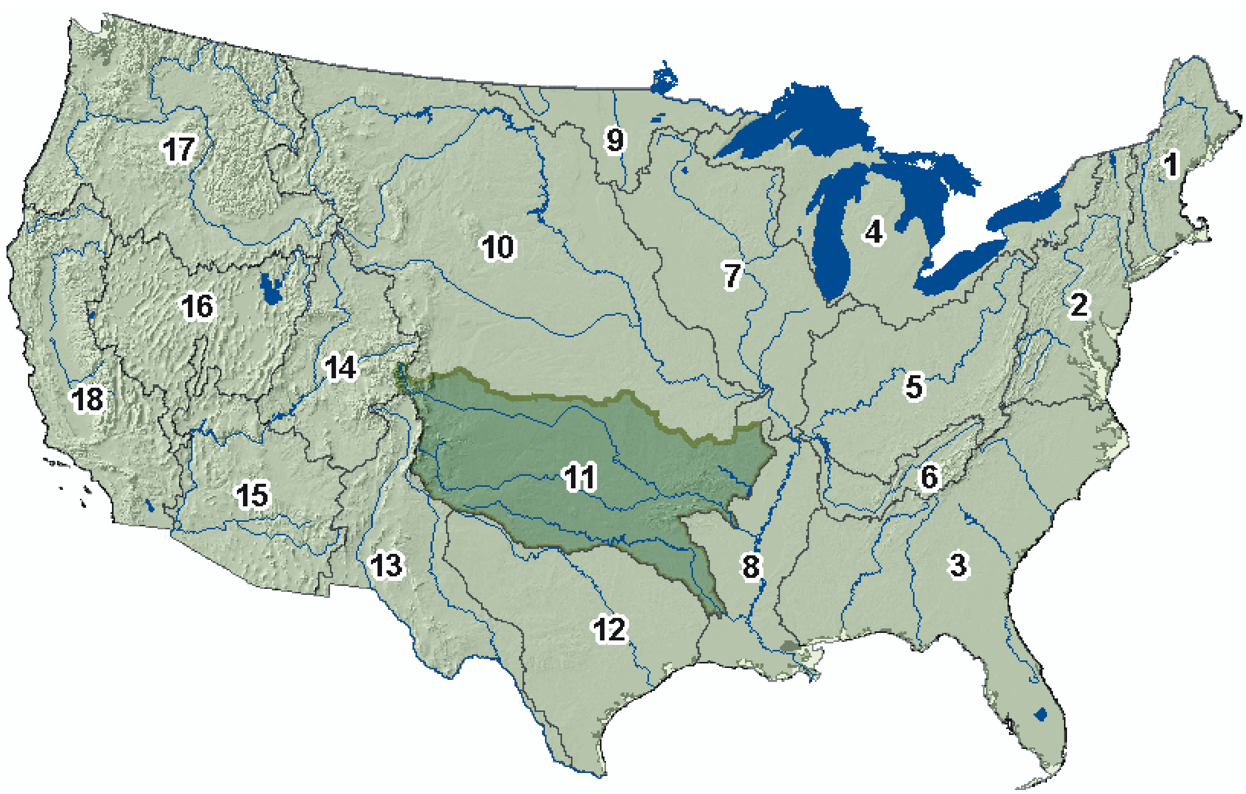


Figure 1. The 18 hydrologic units of the conterminous United States.

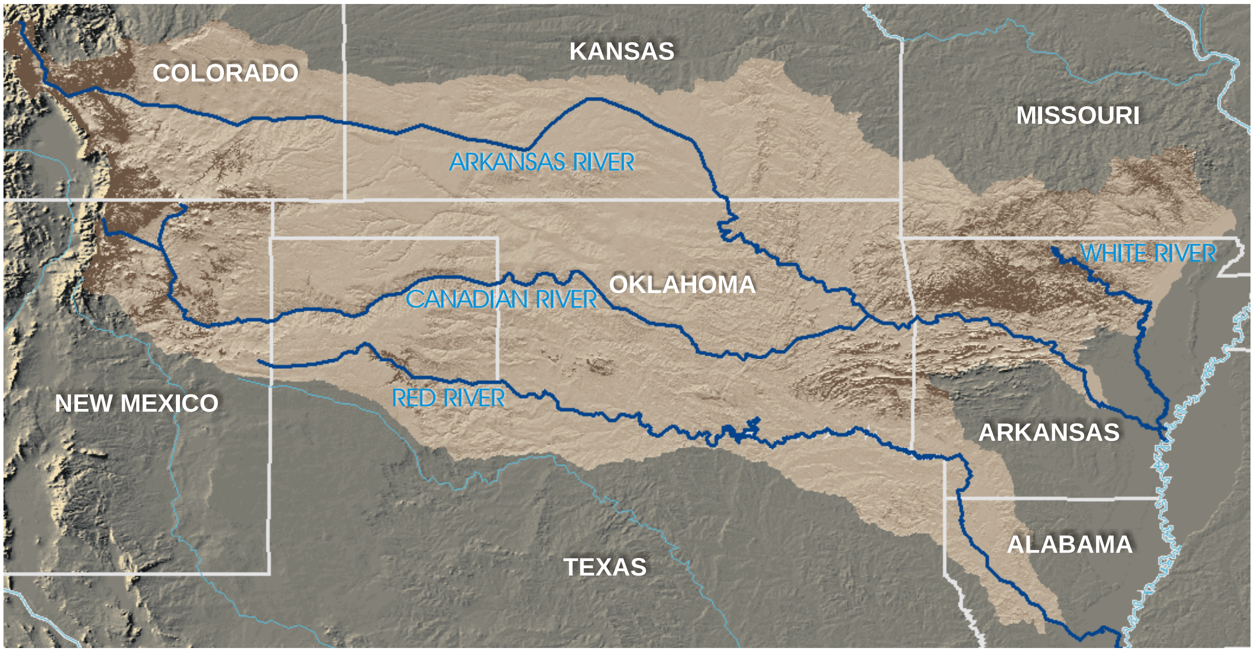


Figure 2. Arkansas White Red Hydrologic Region.

3. TECHNICAL APPROACH

The fundamental approach of this study was to calculate the hydropower potential of every stream reach within the study area. A stream reach was generally the stream segment between two confluences and had an average length of 2 miles. After producing a master set of reach power potentials, this set was filtered to account for waterways excluded from development and to produce subsets based on the operating envelopes of three classes of low head/low power hydropower technologies. Summing the resulting subsets of reach power potentials produced total power potentials of interest. Developed hydropower in the region was deducted to determine "available" power potentials. (Note: The term "available power potential" in this study simply equates to total, nonexcluded power potential minus developed power potential. No economic or development feasibility assessment was performed.)

The calculation of reach hydropower potential requires two values: the reach flow and the hydraulic head corresponding to the elevation difference between the upstream and downstream ends of the reach. The reach flow was the average of the calculated flows at the inlet and outlet of the reach. The flows were calculated using a regression equation in which drainage area, mean annual temperature, and mean annual precipitation were the independent variables. The reach hydraulic head was derived from the hydrography as defined by a digital elevation model.

The subsections that follow describe the details of the various aspects of the technical approach:

- Calculation of reach hydropower potential
- Filtering processes to validate streams, account for excluded waterways, and parse potentials between technology class operating envelopes
- Determination of available power potential based on developed hydropower.

3.1 Calculation of Stream Flow, Hydraulic Head, and Hydropower Potential

The calculation of the stream flow, hydraulic head, and subsequently, hydropower potential requires a three-dimensional representation of the hydrography and related drainage basin information. The three-dimensional hydrography provides the extent of stream networks and the elevation differences required to calculate hydraulic heads. Related drainage basin information provides essential data for the calculation of stream flows. While the National Hydrography Dataset (NHD) provides the best two-dimensional depiction of the U.S. hydrography, it does not provide the required elevation information or related drainage basin information. In order to obtain the required hydrography parameters, the EDNA dataset was used. This dataset provided the needed three-dimensional hydrography in the form of analytically derived stream networks and drainage areas associated with each stream reach that could be summed to produce the drainage basin supplying runoff to points of interest along a stream.

A graphical illustration of the hydrography related information provided by the EDNA dataset is shown in Figure 3. This figure shows synthetic stream reaches each with an associated, local runoff area or catchment shown as a colored area encompassing the reach. Flow rates were calculated at the downstream end of each reach, which has been termed the catchment "pour point." The drainage area supplying runoff at a pour point is equal to the sum of the areas of all of upstream catchments.

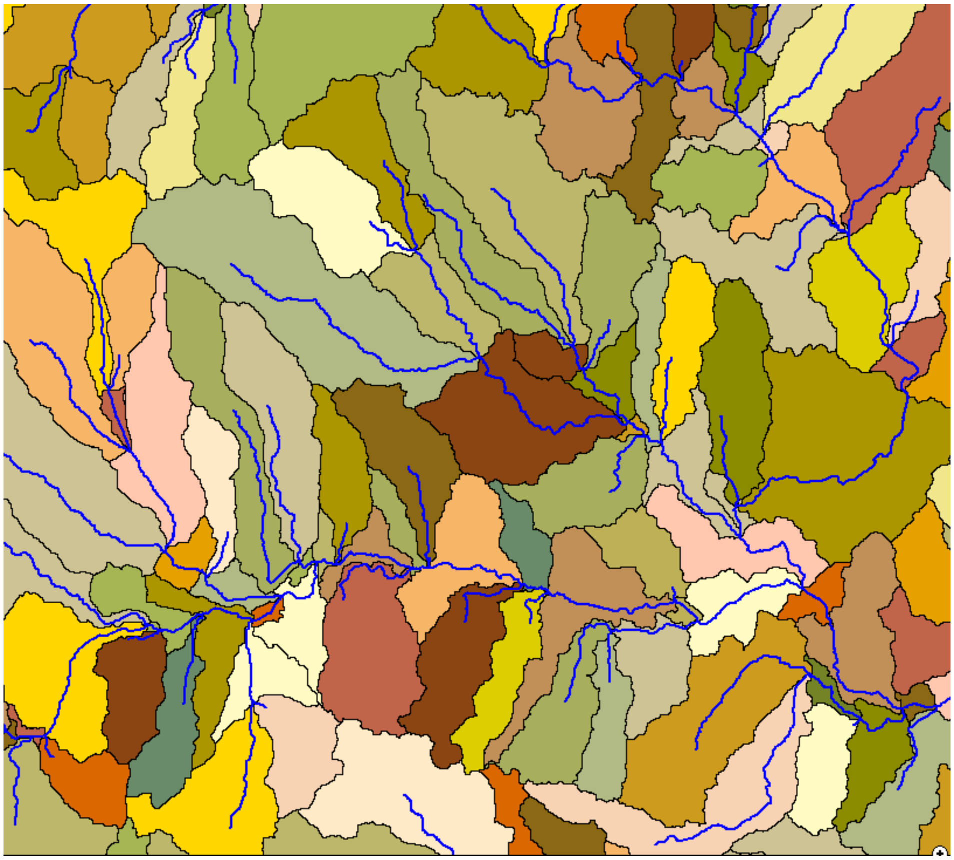


Figure 3. EDNA-derived catchments and synthetic streams.

Mean annual flow rates were calculated using a regression equation developed specifically for the AWR Region (Vogel et al. 1999).

$$Q_{11} = e^{-18.627} * A^{0.96494} * P^{3.8152} * T^{-1.9665}$$

where

Q_{11} = mean flow for a site in the AWR Region in cubic meters/second

A = drainage area in square kilometers

P = mean annual precipitation in millimeters/year

T = mean annual temperature in degrees Fahrenheit times 10.

This equation is based on gaged stream flows within the region. The drainage area used is the sum of the upstream catchment areas. The other two variables, precipitation and temperature, were derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al. 1994). Both temperature and precipitation data contained in the PRISM dataset are in grid format. The cells of the grids are much larger than the cells found in the EDNA dataset; therefore, an averaging function was used to calculate the mean annual precipitation and temperature for each catchment in the EDNA data. The catchment temperature and precipitation values were used to produce an area-weighted value for each drainage area. These values along with the drainage area were used to calculate the flow at the pour point of each catchment.

The hydraulic head associated with each stream reach was obtained using the elevation data in the EDNA dataset. The dataset provided the elevation at the upstream and downstream ends of the reach. The difference of these two elevation values was the hydraulic head or potential energy for the flow in the reach. While this was the correct value for the flow that entered the reach at the upstream end and transited the reach converting potential to kinetic energy, it was not the correct value for the portion of the flow at the reach exit or downstream end that was contributed by runoff from the local catchment. This added flow had hydraulic heads varying from the total reach hydraulic head to zero depending on where the runoff entered the stream. To account for this the following equation was used to calculate the hydropower potential of the reach:

$P = \kappa\,[Q_i * H + (Q_o - Q_i) * H/2]$; $H = z_i - z_o$

where

P	=	power in kilowatts
κ	=	equals (1/11.8)
Q_i	=	flow rate at the upstream end of the stream reach in cubic feet per second
Q_o	=	flow rate at the downstream end of the stream reach in cubic feet per second
H	=	hydraulic head in feet
z_i	=	elevation at the upstream end of the stream reach in feet
z_o	=	elevation at the downstream end of the stream reach in feet.

The first quantity in the square brackets, $Q_i * H$, is the hydropower potential of the flow at the inlet to the reach, which experiences the full hydraulic head of the reach, H (difference between elevations at upstream and downstream ends of the reach). The quantity (Q_o-Q_i) is the part of the reach flow added by runoff from the associated catchment. For this flow, the hydraulic head varies from H to 0 depending on where runoff entered the reach. Therefore, an average value of H/2 was used for the local catchment runoff flow. Algrabic manipulation shows that this equation reduces to:

$P = \kappa H(Q_i+Q_o)/2$

Thus, the reach hydropower potential is equal to a constant times the total reach hydraulic head times the average of the flow rates at the inlet (upstream end) and the outlet (downstream end) of the reach. It is also useful to note that Q_o is the pour point flow for the catchment associated with the reach, and Q_i is equal to the sum of the pour point flows of the catchments immediately upstream of the reach (catchment) of interest.

The calculations described above produced a master dataset that contained the following parameters for each stream reach:

- Reach characteristics
- Related catchment characteristics
- Reach outlet low (catchment pour point flow)
- Reach hydraulic head
- Reach hydropower potential.

This master dataset was subsequently filtered to:

- Remove stream reaches that were not validated using the NHD
- Identify reaches that were excluded from development because of statutory protections
- Identify reaches having hydropower potentials within the low head/low power regime
- Divide low head/low power reaches into three subsets corresponding to the operating envelopes of three classes of low head/low power hydropower technologies.

These filtering operations are described in detail in the subsections that follow.

3.2 Validation of Synthetic Streams

The U.S. Geological Survey performed the processing that produced the Stage 1B version of the EDNA dataset in a consistent manner nationwide. It generally works well for areas having moderate to high relief and well-developed drainage. In certain types of terrain, however, the EDNA Stage 1B processing can create synthetic hydrography that deviates substantially from the actual hydrography. The AWR Region, which was the study area, contains regions in southeastern Colorado, northeastern New Mexico, the Texas and Oklahoma panhandles, and southern Kansas that are characterized by high, semiarid plains with poorly defined drainage, and many playa lakes in basins that do not drain into the regional network. The EDNA Stage 1B processing accounted for some of these disconnected drainages; however, many were artificially connected to the regional drainage network.

Figure 4 shows an overlay of EDNA synthetic streams and hydrography taken from the NHD for the Red River Basin. It is clear from this comparison that some of the synthetic streams reaches are not validated by the NHD and must be removed so as not to inflate the total hydropower potential estimate. To identify these “false” synthetic stream reaches and determine their effect on the regional, total hydropower potential, known stream locations found in the NHD were intersected with the catchments associated with EDNA synthetic streams. This allowed the master dataset to be divided into two subsets: one containing all the reaches whose catchment contained an NHD stream segment and one containing all the reaches whose catchment did not contain an NHD stream segment. The former was considered to be a validated master dataset, while the latter was a dataset containing all the “false” stream reaches showing through in red in Figure 4. While this approach did not guarantee exact conflation of the EDNA synthetic streams with the NHD hydrography, it did ensure that an NHD stream segment existed within the catchment area, averaging 3 square miles that encompassed the synthetic reach.

In order to evaluate the effect of the “false” stream reaches on total hydropower potential, the hydropower potentials of the reaches in the false reach dataset were summed and compared to the sum of the hydropower potentials of all the stream reaches in the master dataset. It was found that 0.8% of the total potential power calculated for the Red River Basin is due to false stream segments. False stream segments account for 0.1% of the total power potential calculated for the White River Basin, while 4.2% of the total potential power calculated for the Arkansas River Basin is due to false stream segments.

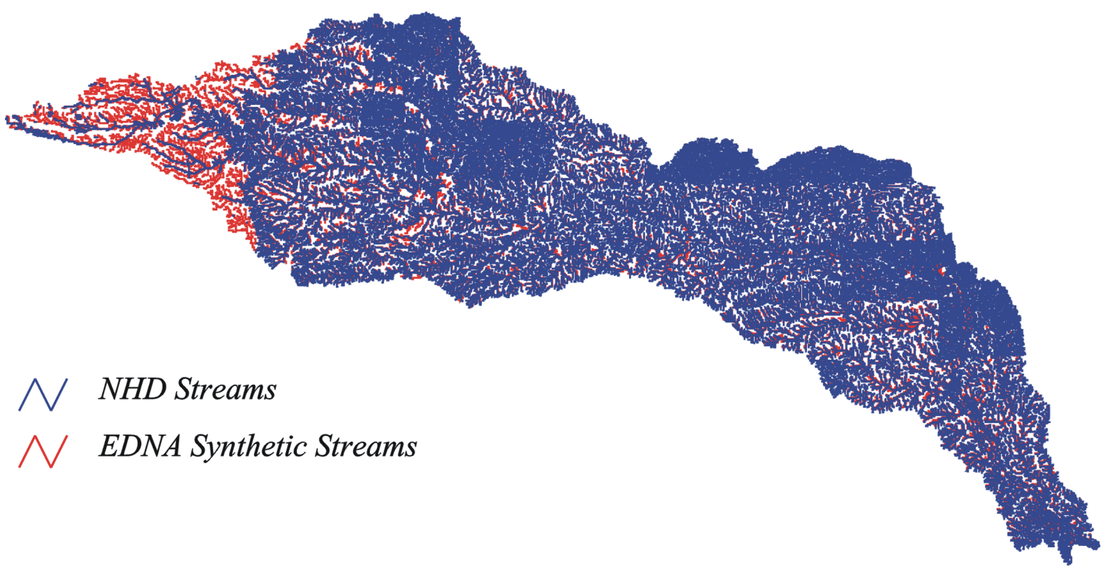


Figure 4. NHD streams overlaying EDNA synthetic streams for the Red River Basin.

3.3 Identification of Excluded Waterways and Hydropower Potential

As a general rule, hydropower development is prohibited in certain protected areas, such as national parks, national monuments, or along federally designated wild and scenic rivers. Protected areas such as these were designated as “excluded areas.” Catchments that overlap any portion of these "excluded areas" were designated as “excluded catchments.” The total hydropower potential associated with the stream reaches in these excluded catchments was calculated, and was subsequently subtracted from the total hydropower potential for the AWR Region, so that it would not contribute to the total available hydropower potential.

3.3.1 Classes of Excluded Waterways

Two geologic information system (GIS) data layers from the National Atlas of the United States were used to locate excluded areas. The first layer, “Federal and Indian Lands,” contains the boundaries of all federal lands in the United States, subdivided into categories such as national parks, national monuments, Indian reservations, military bases, and DOE sites. The second layer, “Parkways and Scenic Rivers,” contains federally protected linear features such as National Wild and Scenic Rivers and National Parkways (such as the Blue Ridge Parkway or the Natchez Trace). Both GIS data layers are available online from the National Atlas of the United States website at ***http://www.nationalatlas.gov/atlasftp.html***.

The two above-mentioned GIS data layers provide comprehensive nationwide information regarding federally protected lands. States, regional jurisdictions, and local jurisdictions have also designated protected areas that are most likely excluded from hydropower development. However, information regarding these protected areas is scattered among numerous state, regional, and local government agencies. Much of this information is not yet in digital format, and much of the digital data is not available online. Determining the boundaries of lands protected by nonfederal agencies would have entailed contacting a large number of agencies within the eight states in the study area and collecting and digitizing multiple paper datasets in a variety of formats. Such an effort was beyond the scope of the project. Therefore, only nationwide datasets of federal lands were used to determine the extent of excluded areas.

The categories of federal lands listed in the GIS dataset “Federal and Indian Lands” were reviewed to determine categories that defined excluded areas. Based on this review, the following categories of federal lands were selected as excluded areas:

- National battlefields
- National historic parks
- National parks
- National parkways
- National monuments
- National preserves
- National wildlife refuges
- Wildlife management areas
- National wilderness areas.

All of the federal lands in these categories were used to create an “excluded federal lands” GIS data layer. Similarly, all national wild and scenic rivers were extracted from the National Wild and Scenic Rivers and National Parkways data layer to create a GIS data layer composed exclusively of Wild and Scenic Rivers. Because the “wild and scenic rivers data layer” contained only the rivers themselves, but no adjoining land, all land within one kilometer of a wild and scenic river reach was designated as an excluded area. These areas were combined with excluded federal lands to create a final “excluded area” GIS data layer that contains the boundaries of all lands to be excluded from hydropower development.

3.3.2 Methodology for Identifying Excluded Stream Reaches

The final excluded area data layer was intersected with the EDNA catchment data layer to identify catchments containing stream reaches that should be excluded from consideration as sources of potential hydropower. Two data subsets resulted: one containing data for reaches that were excluded from hydropower development and one containing data for reaches that were not excluded.

3.4 Determining Developed Hydropower Capacity in the AWR Region

The developed hydropower capacity within the AWR Region was taken from Federal Energy Regulatory Commission's ***Hydroelectric Power Resources of the United States—Developed and Undeveloped (FERC 1992)***. This reference listed 1,966 MW of developed hydroelectric capacity in the region.

3.5 Identification of Low Head/Lower Power Stream Reaches

The low head/low power regime is defined by the following two criteria:

- All hydropower potential less than 100 kW (microhydro)
- Hydropower potential greater than 100 kW but less than 1 MW with hydraulic head less than 30 ft.

The low head/low power regime is shown graphically in Figure 5.

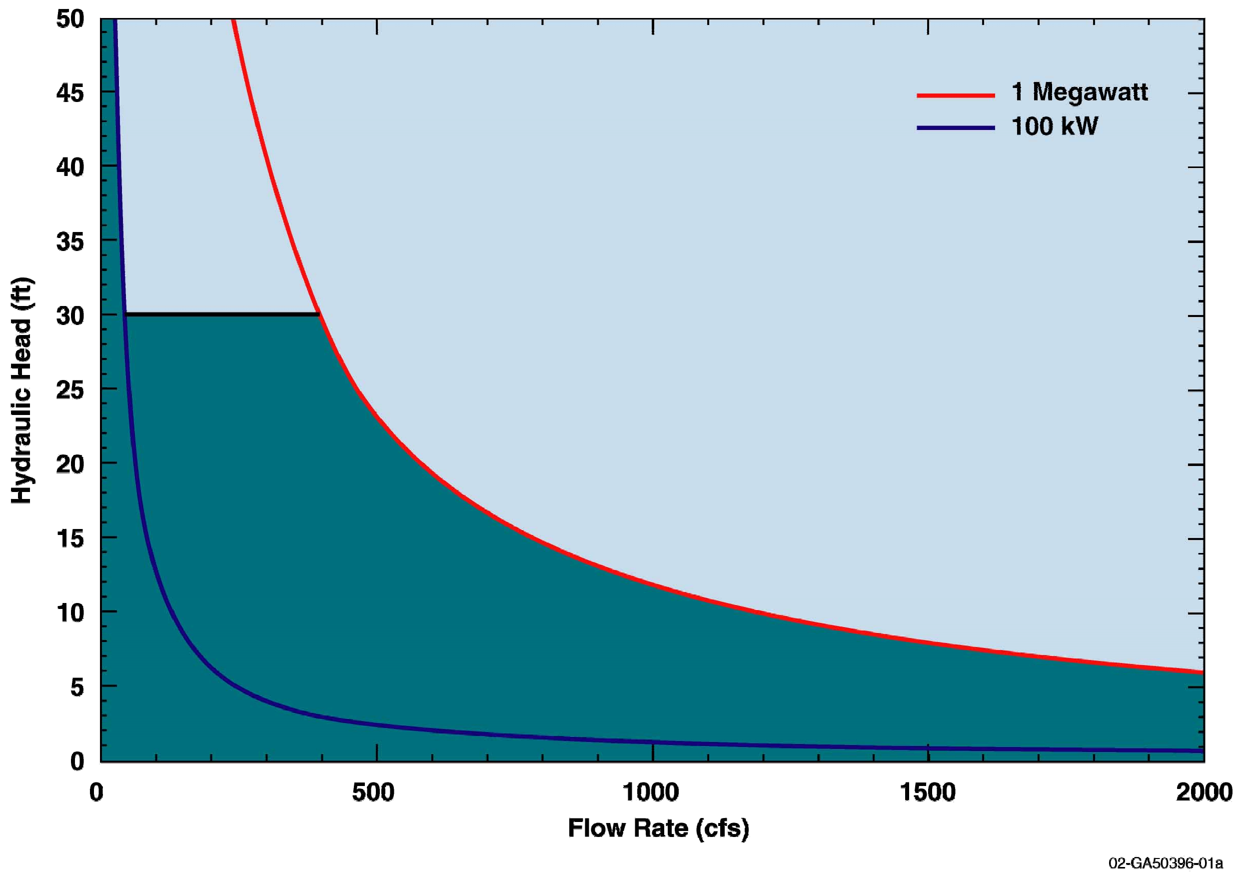


Figure 5. The low head/low power regime.

Standard database query techniques were applied to the validated master dataset described in Subsection 3.2 using the criteria for low head/low power as the selection criteria. This resulted in the identification of stream reaches having hydropower potentials within the boundaries of the low head/low power region. These reaches were also filtered as described in Subsection 3.3 to identify the low head/low power reaches that were excluded and not excluded from development.

3.6 Identification of Stream Reaches Corresponding to the Operating Envelopes of Three Classes of Low Head/Low Power Hydropower Technologies

The low head/low power regime shown in Figure 5 has been divided into the operating envelopes of three classes of low head/low power technologies:

- Microhydro technologies—Power less than or equal to100 kW
- Conventional turbines—Power greater than 100 kW, but less than or equal to 1 MW AND hydraulic head greater than or equal to 8 ft, but less than or to equal to 30 ft.
- Unconventional systems—Power greater than 100 kW, but less than or equal to 1 MW AND hydraulic head less than 8 ft.

These operating envelopes are shown graphically in Figure 6.

Standard database query techniques were applied to the dataset containing low head/low power reaches identified as described in Subsection 3.5. The criteria for defining each of the technology class operating envelopes were used as the selection criteria. This resulted in the identification of stream reaches having hydropower potentials within the boundaries of the operating envelopes. These reach subsets were also filtered as described in Subsection 3.3 to identify the reaches that were excluded and not excluded from development.

3.7 Calculation of AWR Region Total Hydropower Potentials of Interest

Total hydropower potentials of interest were calculated by summing the reach hydropower potentials within each of the datasets that were determined as described in the previous subsections. "Available" hydropower potential was determined by accounting for the corresponding amount of developed hydroelectric capacity. No feasibility analysis was performed to further refine the estimates of available hydropower potential.

3.7.1 Total Hydropower Potential

Summing of the reach hydropower potentials in the validated master dataset described in Subsection 3.2 yielded the estimated total hydropower potential for the region.

3.7.2 Total Excluded And Nonexcluded Hydropower Potential

Summing of the reach hydropower potentials in the excluded and nonexcluded reach datasets described in Subsection 3.3 yielded the estimated total, excluded, and nonexcluded hydropower potentials for the region.

3.7.3 Total Available Hydropower Potential

The total available hydropower potential was determined by subtracting the total developed hydroelectric capacity in the region from the total nonexcluded hydropower potential.

3.7.4 Low Head/Low Power Hydropower Potentials

The total, excluded, nonexcluded, and available hydropower potentials for the low head/low power regime were calculated using the same processing as described above to obtain the total values. However, in this case the dataset containing all low head/low power reaches and the excluded and nonexcluded subsets of this dataset were used. The available potential was equal to

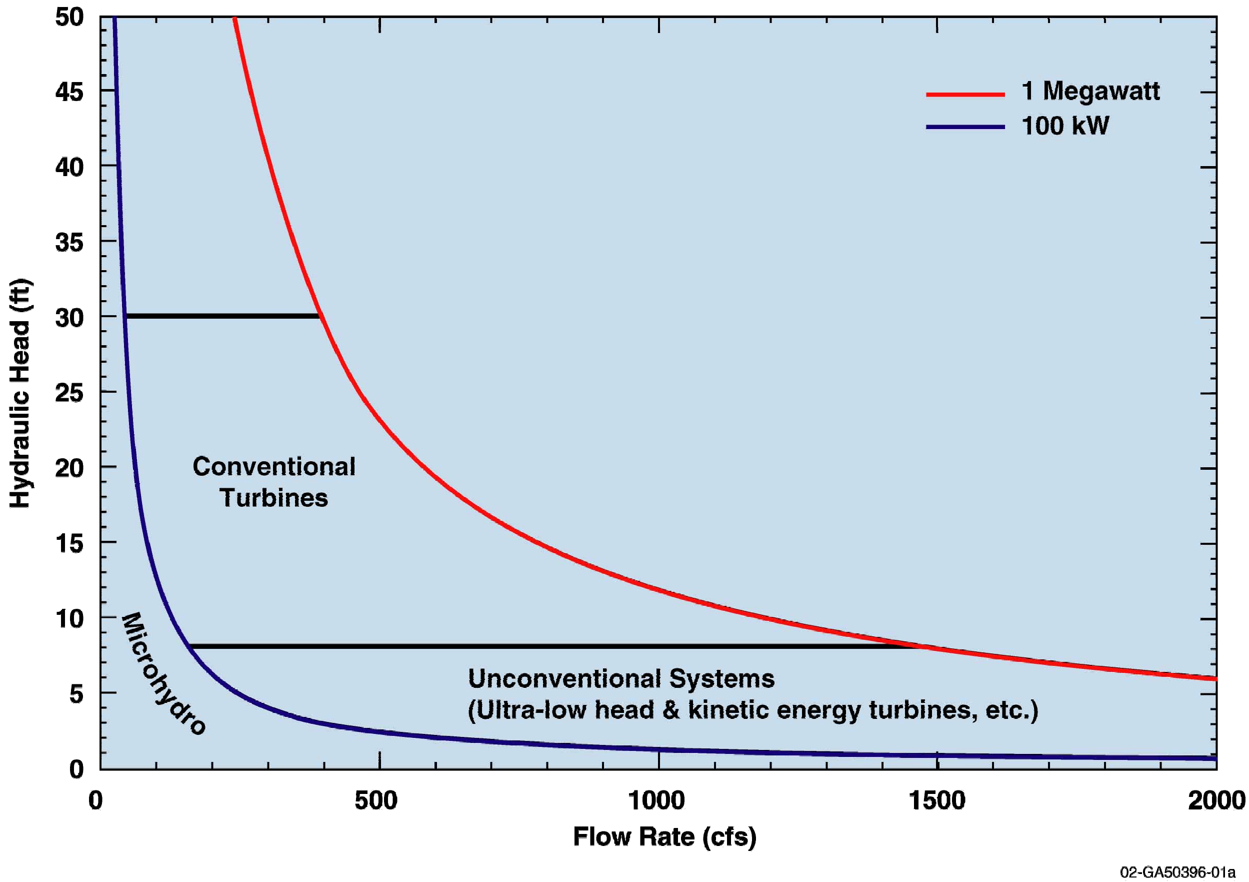


Figure 6. Operating envelopes of three classes of low head/low power hydropower technologies.

the nonexcluded potential, because no developed hydroelectric capacity in the low head/low power regime was listed in the FERC reference.

3.7.5 Hydropower Potentials By Hydropower Technology Class

The total, excluded, nonexcluded, and available hydropower potentials for each hydropower technology class were also calculated using the same processing as described above to obtain the low head/low power values. Each set of hydropower potentials for the three classes was calculated using a set of reach hydropower potentials corresponding to the technology class operating envelope and the excluded and nonexcluded subsets. Available hydropower potential for each technology class was equal to the nonexcluded value because of the absence of developed hydroelectric capacity in the low head/low power regime.

4. RESULTS

The results of the calculations described in Subsection 3.7 are presented in this section. The results are presented in three sets of total hydropower potentials of interest for the AWR Region:

- Total power
- Low head/low power
- Low head/low power by technology class.

The accuracy of the hydropower potential estimates is dependent on the accuracy of the individual stream reach hydropower potentials that were summed to produce total values of interest. The calculated reach flow rates had a standard error of ± 15%. Because of the direct relationship of hydropower potential on flow rate (see Subsection 3.1), the standard error of the reach hydropower potential values was also ± 15%. If the errors are uniformly distributed, the accuracy of a total value produced by summing a large number of reach hydropower potentials may be better than the accuracy associated with the values that were summed.

Table 1 presents a summary of the results with each set of results that are discussed respectively in the subsections that follow.

4.1 Total Hydropower Potential

The sum of all of the validated reach hydropower potentials provided an estimate of 5024 MW of hydropower potential in the AWR Region. FERC has cataloged 1,966 MW of developed hydroelectric capacity in the region. The total hydropower potential of stream reaches excluded from development was 130 MW. Subtracting the developed and excluded hydropower potentials from the total provides an estimate of 2,928 MW of hydropower in the region that has not been developed and is not excluded from development. This available hydropower potential figure is an upper limit and provides an indicator of whether further investigation is warranted. Additional exclusions by state agencies that were beyond the scope of the project to research would most certainly reduce this number. The number would no doubt be further significantly reduced based on the engineering and economic feasibility of specific sites.

The distribution of total hydropower between developed, excluded, and available power is shown graphically in Figure 7. This figure shows that only approximately 40% of the hydropower potential of the region has been developed, which leaves approximately 60% undeveloped. The hydropower potential excluded by federal statute is only 3% of the total, regional hydropower potential.

4.2 Low Head/Low Power Potential

The sum of all the validated reach hydropower potentials having values that fell within the low head/low power regime shown in Figure 5 provided an estimate of 2,021 MW of low head/low power hydropower potential in the AWR Region. FERC did not list any developed hydropower capacity that fell within the

Table 1. Summary of results of hydropower resource assessment of the Arkansas White Red Hydrologic Region.

Power in MW	Total	Developed	Excluded	Available
TOTAL POWER	**5024**	**1966**	**130**	**2928**
LOW HEAD/LOW POWER	**2021**	0	**53**	**1968**
Convential Turbine Technology	754	0	27	727
Unconventional Systems	425	0	11	414
Microhydro	842	0	15	827

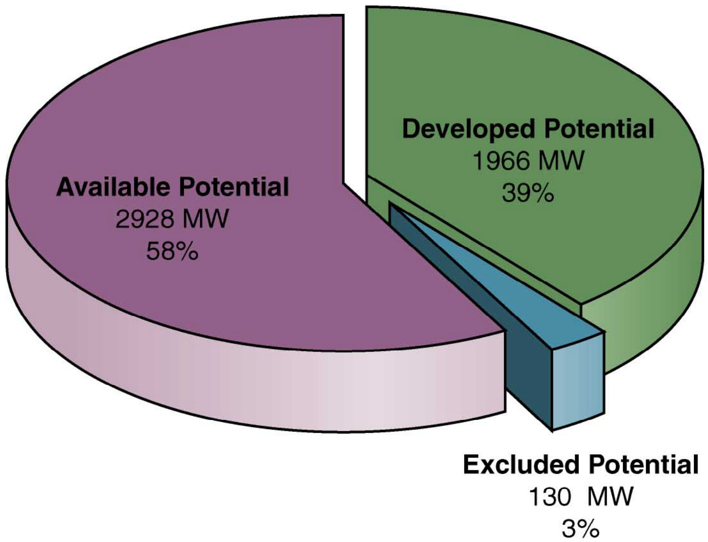


Figure 7. Distribution of total hydropower potential in the Arkansas White Red Hydrologic Region.

low head/low power regime. The total hydropower potential of the reaches that were both low head/low power and were excluded from development was 53 MW. Subtracting the excluded hydropower potential from the total low head/low power potential provides an estimate of 1,968 MW of low head/low power hydropower in the region that has not been developed and is not excluded from development. As mentioned in the previous subsection, this figure is an upper limit and is subject to reductions due to exclusion by state agencies and feasibility assessments.

The distribution of the total, available hydropower potential in the region between the high power (greater than 1 MW), high head/low power (hydraulic head greater than 30 ft and power less than or equal to 1MW, excluding the microhydro operating envelope), and low head/low power is shown graphically in Figure 8. This figure shows that two-thirds of the available hydropower potential is in the low head/low power regime with approximately 24% being high head/low power, and only 9% corresponding to hydropower potentials greater than 1 MW.

4.3 Low Head/Low Power Potential By Technology Class

The validated reach hydropower potentials having values that fell within each of the operating envelopes of the three classes of low head/low power hydropower technologies shown in Figure 6 were summed to provide an estimate of the total hydropower potential associated with technology class. This resulted in estimates of 754 MW, 425 MW, and 842 MW of hydropower potential for conventional turbines, unconventional systems, and microhydro technologies, respectively. The total hydropower potentials of stream reaches excluded from development that fell within each of the operating envelopes were 27 MW, 11 MW, and 15 MW, respectively. Subtracting the excluded potential from the total potential for each technology class resulted in estimates of available hydropower potential of 727 MW, 414 MW, and 827 MW, respectively. As stated in the previous two subsections, these availability estimates do not account for exclusions by state agencies or reductions resulting from feasibility assessments.

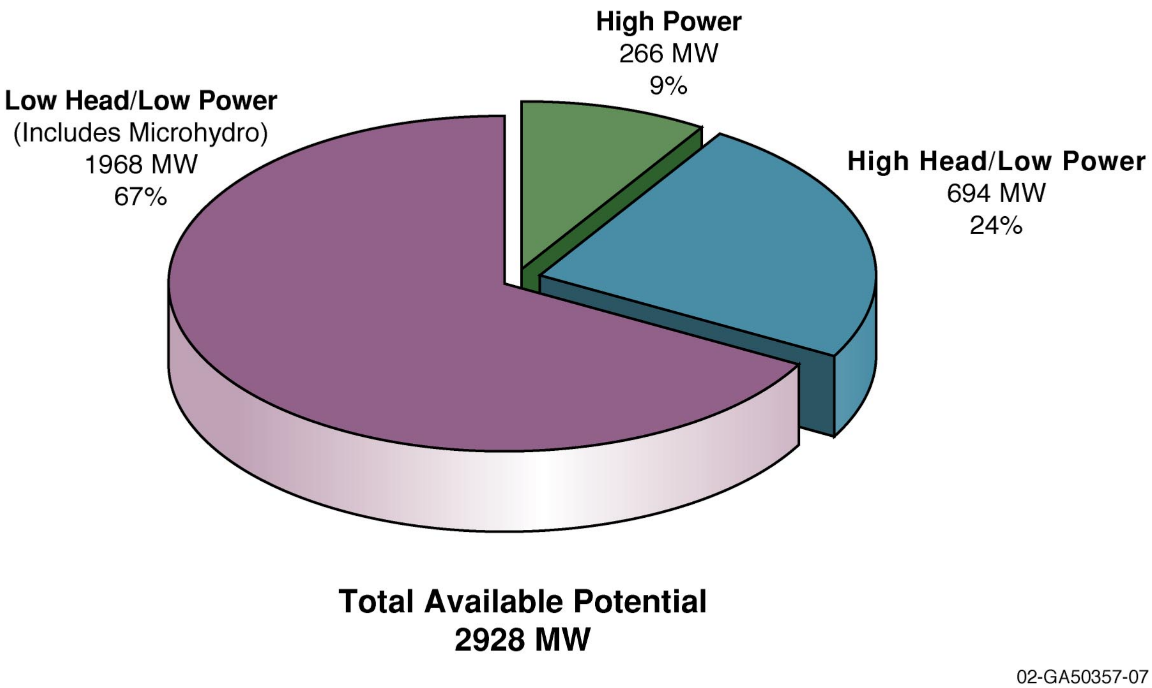


Figure 8. Distribution of available hydropower potential in the AWR Region.

The distribution of low head/low power hydropower potential amongst the three classes of technologies is shown in Figure 9. This figure shows that approximately 40% of the available low head/low power hydropower potential is captured by the operating envelope of conventional turbines which would require relatively little development. Another 40% is captured by the operating envelope of microhydro technologies. The remaining 20% corresponds to unconventional systems.

The geographic locations low head/low power potential sites by technology class are shown in Figure 10. This figure shows a significant density of sites for all three technology classes in the eastern half of the region. Many sites are found along the major rivers throughout the region as expected. It is noteworthy how well the hydropower potential sites, which were derived from the EDNA synthetic stream data, conform to the streams shown on the map, which were included using data from the National Hydrography Dataset.

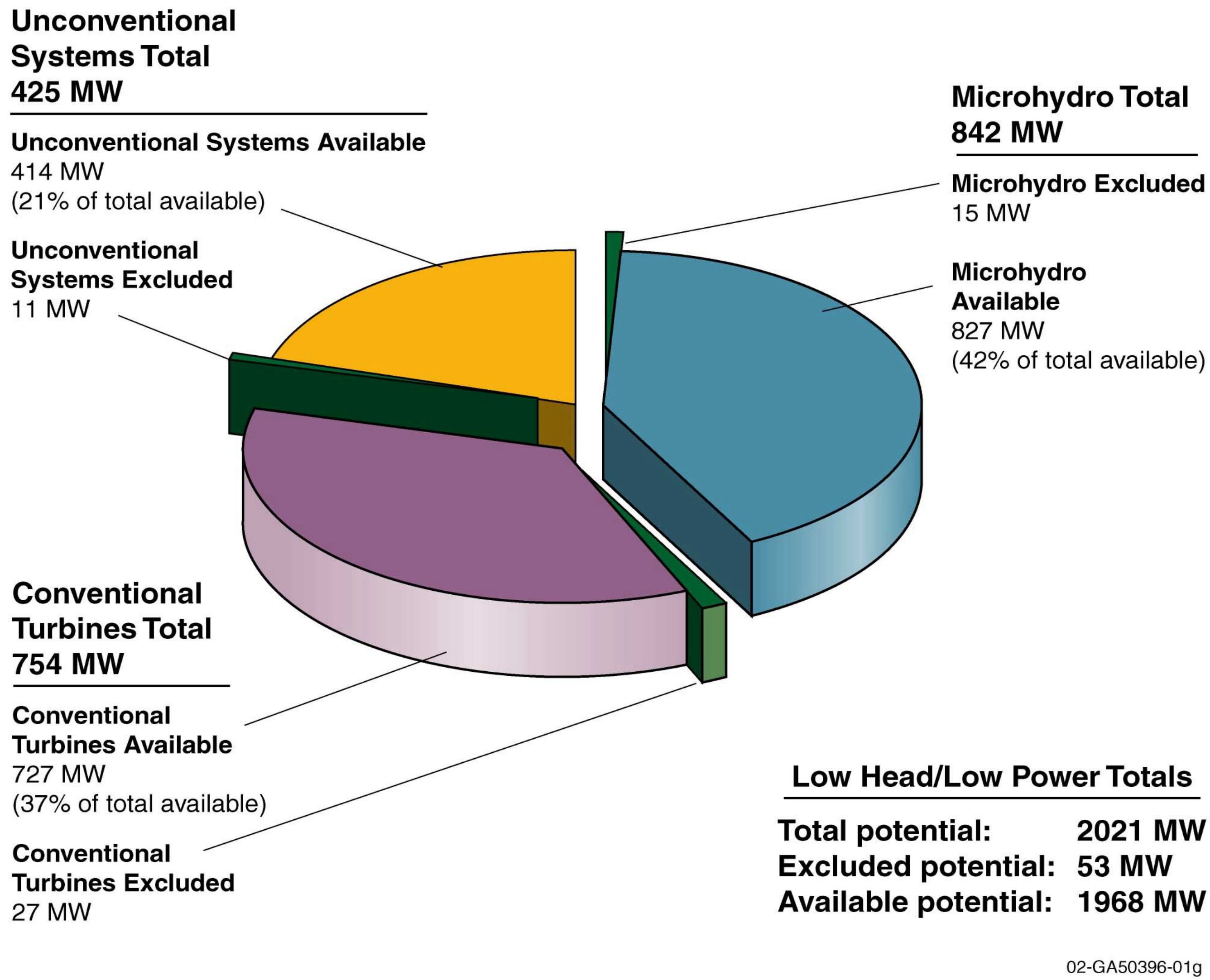


Figure 9. Distribution of low head/low power hydropower potential in the AWR Region amongst three low head/low power hydropower technology classes.

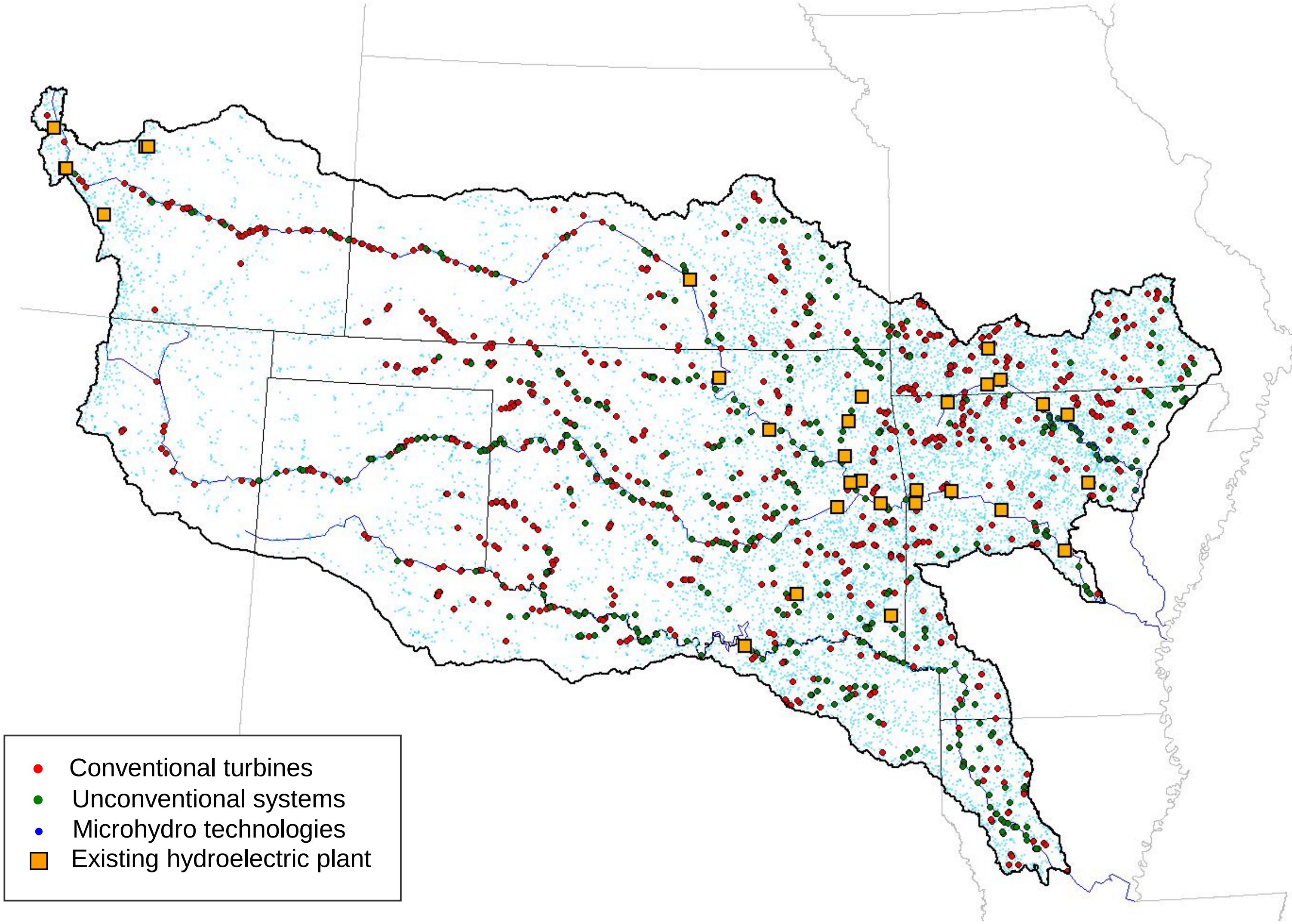


Figure 10. Location of low head/low power hydropower potential sites in the Arkansas White Red Region by technology class.

5. CONCLUSIONS AND RECOMMENDATIONS

This study has demonstrated a viable method for estimating the hydropower potential of a large geographic area. It has resulted in an estimate of approximately 3,000 MW of available hydropower potential in the AWR Region of which two-thirds or 2,000 MW is low head/low power hydropower potential. These estimates are sufficiently large to warrant further research regarding possible siting of low head/low power hydropower installations in the region. The study has shown that approximately 40% of the available low head/low power hydropower potential falls with the operating envelope of existing, conventional turbine technology. Thus this fraction of the available hydropower potential could be realized without investments in basic research. Sixty percent of the available hydropower potential corresponds to technologies (microhydro and unconventional systems) that would require additional research and development; although, some units currently exist that could be put into service.

The success of this pilot study has shown that it is possible to obtain an estimate of the hydropower potential of the entire United States that is based on minutely detailed hydrography.

Application of the technical approach developed in this study to each of the 18 hydrologic units in the conterminous U.S. and ultimately the State of Alaska will allow assessment of the available hydropower potential of each region and identification of the type of technology best suited to realize that potential. A composite of these regional results will provide a spatial distribution of available hydropower potential in the conterminous U.S. as well as estimate of total available U.S. potential. Given the demonstrated possibility of obtaining this important, fundamental information, it seems reasonable to apply the developed technical approach to the 17 remaining hydrologic regions in the conterminous U.S. and to the State of Alaska when the required basic data for that state becomes available. Prior to launching the effort to perform similar assessments of all 17 remaining regions, it is recommended that one more region be assessed and the results evaluated before the full-scale effort is undertaken. The region recommended for this confirmatory assessment is the Pacific Northwest Hydrologic Region (HUC 17) shown in Figure 11. This region is recommended because of its variety of topography and hydrography, which contrast with that of HUC 11.

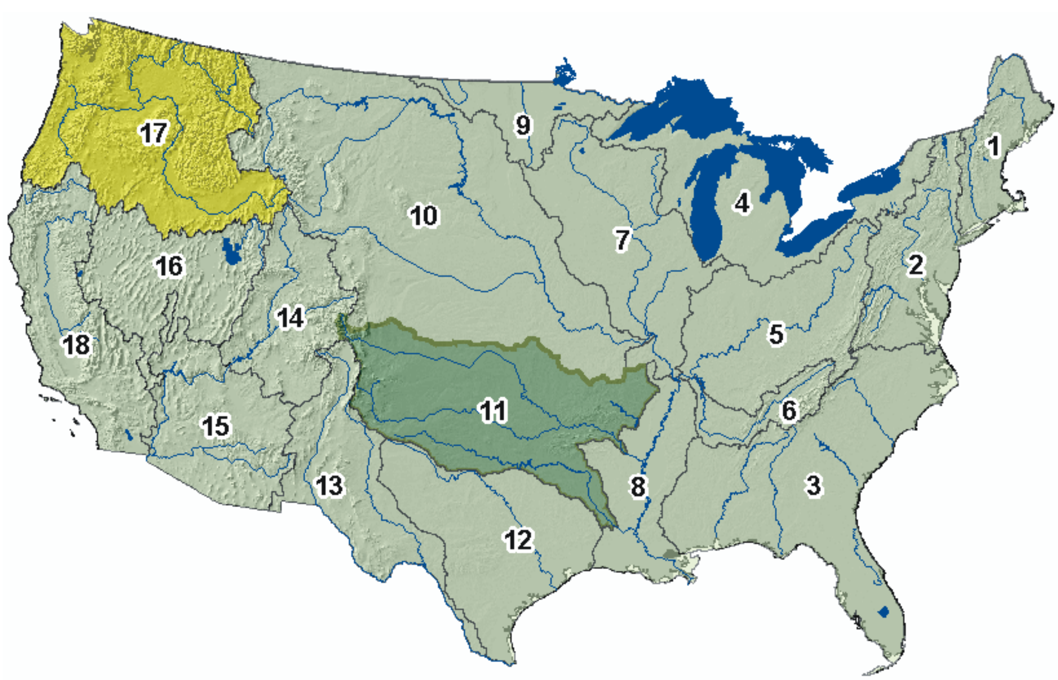


Figure 11. Location of the Pacific Northwest Hydrologic Region (HUC 17).

Early in the expanded study, it is recommended that results of stream reach flow rate and hydropower potential calculations be benchmarked against known, gauged flows and installed hydropower capacity. The study should be driven by the availability of EDNA synthetic hydrography that has been validated by the U.S. Geological Survey in its ongoing efforts to obtain correlation between EDNA hydrography and that provided by the more accurate National Hydrography Dataset. If possible, equations that predict median rather than mean annual stream flow should be used to obtain better temporal estimates of hydropower potential.

6. REFERENCES

Daly, C., R. P. Neilson, and D. L. Phillips, 1994, "A Statistical-Topographic Model For Mapping Climatological Precipitation Over Mountainous Terrain," ***Journal of Applied Meteorology***, 33, 1994, pp. 140–158.

Federal Energy Regulatory Commission, 1992, ***Hydroelectric Power Resources of the United States—Developed and Undeveloped***, Washington: 1 January 1992, p. 80.

Vogel, R. M., I. Wilson, and C. Daly, 1999, "Regional Regression Models of Annual Streamflow for the United States," ***Journal of Irrigation and Drainage Engineering***, May/June 1999, pp. 148–157.